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Research Article

Contention- and Interference-Aware Flow-Based Routing in Wireless Mesh Networks: Design and Evaluation of a Novel Routing Metric

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As the popularity of IEEE 802.11-based Wireless Mesh Networks (WMNs) grows, end users of these environments demand better performance and quality of service (QoS). However, the Medium Access Control (MAC) layer of the IEEE 802.11 standard was not initially designed to provide either multihop or QoS capabilities. Therefore, the performance of IEEE 802.11-based WMNs is not optimal. One approach that can mitigate the limitations of IEEE 802.11-based WMNs relies on routing flows through appropriate paths according to: (i) the characteristics of the flows, (ii) the quality of the WMN links, (iii) the contention in transmission, and (iv) the interference in reception. Considerable research effort has been devoted to this topic. However, as we argue in this paper, a comprehensive solution is still needed. This paper presents the Weighted Contention and Interference routing Metric (WCIM). Extensive simulation results show that WCIM outperforms state-of-the-art solutions.

1. Introduction

Wireless Mesh Networks (WMNs) have gained popularity as a technology for wireless networking. IEEE 802.11-based mesh networking has been the forerunner in topic research, product development and network deployment of wireless mesh [1]. Its popularity has been fueled by the vast number of cheap, commercial, off-the-shelf IEEE 802.11 products available on the market, and by the fact that IEEE 802.11 standards [2] are the de-facto radio interface for Wireless Local Area Networks (WLANs). As the popularity of WMNs grows, end users demand better performance. However, the Medium Access Control (MAC) layer of the IEEE 802.11 standard was not initially designed to provide multihop capabilities [3], therefore, it does not appropriately handle the issues of medium sharing and interference in these environments. In consequence, performance suffers significant degradation [4, 5], which is further challenged by radio propagation uncertainty.

In WMNs, a data flow can suffer inter and intra-flow interference throughout its route [6]. Interflow interference occurs when several flows being transmitted by close links compete for the same channel. On the other hand, a node transmitting packets of a given flow suffers intra-flow interference when other links in the path of that flow transmit packets of the same flow, using the same channel. Both types of interference are the main cause of the severe performance degradation of WMNs with the increase of active flows and the length of the paths.

One approach that can mitigate the limitations mentioned above is the routing of flows through appropriate paths according to an adequate routing metric. Considerable research effort has been devoted to the design of routing metrics by taking into account at least some of the following aspects [6–18]: (i) the characteristics of the flows, (ii) the quality of the WMN links, (iii) the contention in transmission and (iv) the interference in reception. Nevertheless, as we argue in this paper, a comprehensive solution is still needed. In this paper, we present the following contributions:

(i) a comprehensive study of the main routing metrics for WMNs,

(ii) the design of the Weighted Contention and Interference routing Metric (WCIM),

(iii) an evaluation of WCIM by means of extensive simulation in single-radio scenarios, comparing its performance with that of state-of-the-art routing metrics. Results show the benefits of WCIM in a variety of scenarios.

The remainder of the paper is organized as follows. Section 2 lists the requirements that a WMN routing metric should fulfill and surveys the most relevant routing metrics for WMNs. Section 3 presents the design of WCIM, while its flow based routing scheme is described in Section 4. Section 5 presents the simulations for evaluating WCIM solution, focusing on the comparison with other state-of-the-art routing metrics. Finally, Section 6 concludes the paper with a summary of our work and a discussion of future research directions.

2. Routing Metrics for WMNs

This section studies routing metrics for WMNs. Section 2.1 lists a set of routing metric requirements. Section 2.2 reviews the most relevant routing metrics for WMNs, and Section 2.3 discusses the presented metrics, based on the requirements identified in Section 2.1.

2.1. Routing metric requirements. The following is a list of requirements for routing metrics in WMNs.

(1) Link-Awareness. The routing metric should include mechanisms for obtaining information about link characteristics, such as transmission bit rate and error rate.

(2) Load-Awareness. Node and channel congestion are proportional to the load of the nodes, which can be estimated on the basis of the number of active routes, queue length, the transmission rate of active flows, and so forth.

(3) Contention and Interference-awareness. Contention in transmission and interference in reception affect the performance of the flows in 802.11 WMNs.

(4) Flow Differentiation. Capturing the characteristics of a flow (e.g., packet size and flow rate) is necessary in order to route flows according to their requirements [19].

Other requirements may apply for WMNs with particular characteristics. For instance, channel-awareness is required in multiradio WMNs in order to consider properly the impact of contention and interference on performance [20]. On the other hand, energy awareness is required for networks whereby at least some nodes are battery-operated. Without loss of generality, we focus our analysis on single-radio back-haul, fixed and power-affluent WMNs, which are the most common ones in commercial and community deployments.

Table 1: Notations used in this paper.

Notations	
ETX_{ij}	ETX metric of link from node i to node j
ETT_{ij}	ETT metric of link from node i to node j
S	Fixed packet size of a probe packet
LR_{ij}	Nominal transmission bit rate of link ij
O	PHY and MAC layer overhead
N_1^i	One-hop neighbors of node i
N_2^i	Two-hop neighbors of node i
N_{ij}	$N_1^i \cup N_1^j$
NI_{ij}	Interfering $N_1^i \cup N_1^j$
P_k	Average packet size of the kth flow
FR_k	Sending rate of the kth flow
$\alpha_{ij,k}$	Efficiency of link ij for the flow k
CN^i	Percentage of channel occupied by node i
$\mathrm{BW}_{ij,k}$	Bandwidth of the link ij for the kth flow
CL_{ij}	Level of contention in transmission at link ij
N_1^j/N_1^i	One-hop neighbors of node j which are not one-hop neighbors of node i
IL_{ij}	Level of interference in reception at link ij
N_2^j/N_1^i	Two-hop neighbors of node j which are not one-hop neighbors of node i

2.2. Review of Routing Metrics. The number of hops between two nodes has been the de facto metric of the first routing protocols for wireless multihop networks. However, in recent years, several alternative routing metrics have been proposed to take into account other relevant network characteristics. We classify routing metrics as load unaware and load aware. Load-aware metrics consider the transmission activity of network nodes in order to balance active flows and avoid congestion or interference. For the sake of fair comparison, parameters related with multiradio in channel-aware metrics are not analyzed. All the following routing metrics are designed in an additive form. For a summary of the notations used in this paper, the reader may refer to Table 1.

2.2.1. Load-Unaware Routing Metrics. The Expected Transmission Count (ETX) [7] metric was one of the first attempts to increase performance in WMNs as an alternative to the hop count metric. This metric estimates the expected number of transmission attempts for a packet through a link. ETX has been widely adopted, since a node only needs to compute the packet error probability in transmission and reception, denoted in (1) as d_i and d_j, respectively, to obtain the link cost, denoted by ETX_{ij}. Both link directions are considered, since successful frame transmission requires the reception of an ACK frame in many cases, as in 802.11 CSMA/CA.

$$\mathrm{ETX}_{ij} = \frac{1}{d_i \times d_j}. \tag{1}$$

The Expected Transmission Time metric (ETT) [8] improves the ETX metric, as it aims to take into account the link bandwidth, thus favoring fast links with low error rates. In order to achieve this goal, ETT_{ij} estimates the time required for the transmission of a packet through the link between nodes i and j. ETT_{ij} builds on the basis of ETX_{ij}, the transmission bit rate of the link, LR_{ij}, and the size of a probe packet, S, as shown in (2)

$$\mathrm{ETT}_{ij} = \mathrm{ETX}_{ij} \times \frac{S}{\mathrm{LR}_{ij}}. \tag{2}$$

The Airtime Link Metric (ALM), a routing metric defined in the IEEE 802.11s draft standard [9], estimates the channel following principles similar to those of ETT. ALM estimates the channel time required for packet transmission through a link [10]. Equation (3) shows the metric definition, where O denotes the physical and MAC layer overheads, S is the size of the probe frame, LR_{ij} is the transmission bit rate and e_f is the frame error rate for the probe frame.

$$\mathrm{ALM}_{ij} = \left[O + \frac{S}{\mathrm{LR}_{ij}}\right]\frac{1}{1 - e_f}. \tag{3}$$

Like the ALM, the Medium Time Metric (MTM) is defined as an estimation of the medium transmission time of a packet through a path [11]. A vector extension to MTM has been proposed, where different packet sizes are defined to calculate various metric values [12]. Consequently, different traffic types can be classified according to their packet lengths and routed via different paths if necessary.

The Metric of Interference and Channel-switching (MIC) of a link has been defined as an extension to the ETT metric [6]. In single-radio WMNs, MIC is defined as shown in (4), where it considers the interflow interference by scaling its ETT_{ij} metric by the number of one-hop neighbors of nodes i and j, N_{ij}.

$$\mathrm{MIC}_{ij} = \mathrm{ETT}_{ij} \times N_{ij}. \tag{4}$$

The Exclusive Expected Transmission Time (EETT) metric is defined in a similar way to MIC [13]. However, in this case the cost of a link ij, which is denoted by EETT_{ij} is computed as the sum of the ETT metrics of all the links in the interfering set of link ij, denoted by $IS(ij)$, including link ij itself.

$$\mathrm{EETT}_{ij} = \sum_{\forall l \in \mathrm{IS}(ij)} \mathrm{ETT}_l \tag{5}$$

While the MIC metric captures the impact of link ij on other links, EETT considers the impact of all the links that compose the interfering set of link ij. Thus, since the ETT metric of a link also determines its channel time consumption (i.e., slower links require more channel time), EETT represents the congestion or interference on a specific interfering set with greater accuracy. However, neither MIC nor EETT are load aware metrics, thus assuming that all the neighbors of each node continuously contribute to interflow interference, which may not accurately reflect network behavior.

2.2.2. Load-Aware Routing Metrics. Initial proposals of load aware routing metrics for ad hoc networks defined very simple load models. For instance, some routing metrics estimate the node load as the number of queued packets of the node [14]. Another example is a metric used in Load-Balanced Ad-hoc Routing (LBAR) [15]. This protocol uses the number of active routes of a node and its neighbors for estimating congestion, assuming that all routes are traversed by flows with identical characteristics, which may not be true in a real network.

Several load aware routing metrics assume usage of an IEEE 802.11 MAC protocol and aim to include the characteristics of this protocol in the metric computation. The Interference Aware Routing (IAR) metric [16] uses MAC-level measurements to estimate link congestion due to interference from other nodes. The cost of a link ij, IAR_{ij}, is defined by the following Equations:

$$\begin{aligned} \mathrm{IAR}_{ij} &= \frac{1}{1-\alpha_{ub}} \times \frac{S}{\mathrm{LR}_{ij}}, \\ \alpha_{ub} &= \frac{T_{\mathrm{Wait}} + T_{\mathrm{Collision}} + T_{\mathrm{Backoff}}}{T_{\mathrm{Wait}} + T_{\mathrm{Collision}} + T_{\mathrm{Backoff}} + T_{\mathrm{Success}}}, \end{aligned} \tag{6}$$

where T_{Wait}, $T_{\mathrm{Collision}}$, T_{Backoff} and T_{Success} quantify the time spent in the respective states of packet transmission at MAC-level. These time values are obtained via passive measurements (i.e., by using active transmissions in the node) or by active probing, which adds protocol overhead.

In single-radio WMNs, the Interference-Load Aware (ILA) metric [17] considers interflow interference by means of the Metric of Traffic Interference (MTI). ILA calculates the cost of a link ij, MTI_{ij}, as follows:

$$\mathrm{MTI}_{ij} = \begin{cases} \dfrac{\mathrm{ETT}_{ij}}{\mathrm{ETT}_{\min}} & \text{if } \mathrm{NI}_{ij} = 0, \\[2ex] \dfrac{\mathrm{ETT}_{ij} \times \mathrm{AIL}_{ij}}{\mathrm{ETT}_{\min} \times \mathrm{AILmin}} & \text{if } \mathrm{NI}_{ij} \neq 0, \end{cases} \tag{7}$$

where NI_{ij} is the number of one-hop neighbors of nodes i and j with active flows. If there are interfering nodes, the MTI_{ij} scales the ETT_{ij} by the Average Interference Load (AIL) affecting transmissions from node i to j, denoted by AIL_{ij}. $ETT_{\min}$ and $AIL_{\min}$ are the smallest values in the network for ETT and AIL, respectively, and are used for scaling purposes. The AIL_{ij} is defined in (8), where IL_k denotes the interference load, that is, the load of the kth neighbor that causes interference on transmissions between i and j

$$\mathrm{AIL}_{ij} = \frac{\sum_{\forall k \in \mathrm{NI}_{ij}} \mathrm{IL}^k}{\mathrm{NI}_{ij}}. \tag{8}$$

The interference parameter IL^k is defined as the number of bytes transmitted [17]. This definition does not capture the effect of different link bit rates on interference, that is, flows transmitted at low link rates consume more channel time than those transmitted at higher rates. In addition, since $\mathrm{AIL}_{ij}/\mathrm{AIL}_{\min}$ is always greater than 1, the MTI_{ij} parameter defined in (7) grows very fast with interference. Hence, the ILA metric favors the selection of long paths through links totally free of interference, while the metric discards shorter routes composed of links with a low interference level.

iAWARE is an interference-aware routing metric defined for a multiradio routing protocol [18]. The single-radio version of the iAWARE routing metric of a path is calculated as follows:

$$\mathrm{iAWARE}_{ij} = \frac{\mathrm{ETT}_{ij}}{\mathrm{IR}_{ij}}, \quad 0 < \mathrm{IR}_{ij} \leq 1. \tag{9}$$

iAWARE basically weights the ETT metric of link ij by the corresponding Interference Ratio (IR), denoted by IR_{ij}. This parameter is calculated as the minimum value of the ratio between the Signal to Interference and Noise Ratio (SINR) and the Signal to Noise Ratio (SNR), sensed by both nodes forming the link ij. In an experimental study using two-radio nodes, the iAWARE metric provided better throughput than ETT and MIC metrics [18]. However, SNR and SINR values were obtained from radio interface measurements, which makes the metric dependent on the hardware used. In addition, since the IR_{ij} parameter is defined as the minimum IR sensed by both nodes forming the link, it only captures contention in sending or interference in receiving (i.e., both phenomena cannot be dealt with simultaneously).

2.3. Routing Metrics Discussion. Table 2 summarizes the properties of the routing metrics presented for WMNs, based on the requirements shown in Section 2.1. Interference and load unaware routing metrics improve the simple hop count metric by introducing link quality information. In multirate WMNs, the link bit rate information used by metrics like ETT or ALM is fundamental in order to avoid slow links. However, such metrics can also concentrate traffic on the highest quality links, which can produce congestion. Interference-aware metrics like MIC or EETT may help to mitigate this problem by routing flows through links with a lower probability of becoming congested. MIC searches for links sharing the channel with few neighbors, while EETT also takes into account the channel time consumption of the nodes competing for the same channel. Nevertheless, since both metrics are load unaware, they still tend to concentrate traffic on some specific links and may lead to congestion.

On the other hand, load aware metrics can better distribute flows through the network. ILA extends MIC by using information about the active transmissions of its neighbors, thus favoring the selection of paths composed of links totally free of interference. On the other hand, iAWARE takes advantage of cross-layer feedback to obtain the interference level of a node. However, this metric does not fully capture sender-side interference, which results in back-offs or interfered ACKs [18].

From the analysis of the routing metrics presented above, we conclude that a comprehensive solution considering all the relevant phenomena affecting the performance of a path is still needed. In the following section we introduce the Weighted Contention and Interference routing Metric (WCIM), which aims at addressing the limitations of the aforementioned routing metrics.

3. WCIM Routing Metric

The objective of the WCIM routing metric is to select paths according to: (i) the flow characteristics, (ii) the quality of the WMN links, (iii) the contention in transmission and (iv) the interference in reception. Our purpose is to include all of these factors in an accurate yet simple way. First, we define the metrics for estimating channel occupancy and how they are used to model the contention and interference level of a link. Then, the definition of the WCIM metric is presented. Finally, the section discusses requirements on the routing protocol to be used in conjunction with WCIM.

3.1. Channel Occupancy. The parameter describing the load of a node must increase with the sending rate of the active flows of that node. In addition, in order to weight the amount of channel time consumed, the capabilities of the link being used by the flow must be considered. Traffic routed through a slow link captures the channel for a long time in each transmission attempt. Likewise, links with a high error ratio lead to a high number of retransmissions and channel consumption. Therefore, we define CF_k^{ij} as the percentage of channel occupied by the kth flow when routed by node i to next-hop j as follows:

$$\mathrm{CF}_k^{ij} = \frac{\mathrm{FR}_k}{\mathrm{BW}_{ij,k}}, \tag{10}$$

where FR_k defines the sending rate of the kth flow and $\mathrm{BW}_{ij,k}$ denotes the bandwidth of link ij for the kth flow. The bandwidth is computed as shown in (11)

$$\mathrm{BW}_{ij,k} = \frac{\mathrm{LR}_{ij}}{\alpha_{ij,k} \times \mathrm{ETX}_{ij}}, \tag{11}$$

where the nominal link bit rate LR_{ij} (e.g., 6 Mbps, 12 Mbps, etc.) is divided by the ETX metric of the link, ETX_{ij}, and by the parameter $\alpha_{ij,k}$. This coefficient reflects the efficiency of the nominal link bit rate LR_{ij} in relation to the average packet size P_k (in bytes) of the kth flow, as shown in (12)

$$a_{ij,k} = \frac{O + (P_k + O_h) \times 8/\mathrm{LR}_{ij}}{P_k \times 8/\mathrm{LR}_{ij}}, \tag{12}$$

where O_h is the MAC header in bytes and O denotes the rest of the MAC and physical layers overhead (i.e., the preamble transmission, DIFS, SIFS, ACK transmission, etc.) in time units. In short, (10) provides the portion of actual link bandwidth or channel time consumed by the kth flow of node i, which gives a maximum value of 1 if flow k consumes the whole bandwidth of link ij.

Next, we define the percentage of channel occupied by node i, CN^i, as the sum of the channel occupancy of all its NF^i active flows, as shown in (13). Thus, this parameter provides the portion of channel time consumed by node i and its maximum value is 1 (which corresponds to the channel being used at its maximum capacity)

$$\mathrm{CN}^i = \sum_{\substack{k=1 \\ j \in N_1^i}}^{\mathrm{NF}^i} \mathrm{CF}_k^{ij}. \tag{13}$$

Table 2: Comparison of routing metrics.

Routing metric	No. hops	Bit error rate	Link bit rate	Load-awareness	Interflow interference	Flow diff.	Evaluation
Hop Count	yes	no	no	no	no	no	Experimental
ETX	yes	yes	no	no	no	no	Experimental
ETT	yes	yes	yes	no	no	no	Experimental
ALM	yes	yes	yes	no	no	no	Experimental
MTM	yes	yes	yes	no	no	yes(1)	Experimental
MIC	yes	yes	yes	no	N_{ij}	no	Simulation
EETT	yes	yes	yes	no	IS(ij)	no	Simulation
LBAR	yes	no	no	Number of active routes	N_1^i	no	Simulation
IAR	yes	yes	yes	Busy time percentage	Measured	no	Simulation(2)
ILA	yes	yes	yes	Bytes transmitted	NI_{ij}	no	Simulation
iAWARE	yes	yes	yes	Interference Ratio: SNIR/SNR	Sensed: Sender- or Receiver-side	no	Experimental(2)

(1) Differentiation by packet sizes using a vector extension [12].
(2) Requires radio interface measurements.

3.2. Contention Level in Transmission. Contention in transmission depends on the Carrier Sensing mechanism of CSMA/CA. IEEE 802.11 cards employ two main Clear Channel Assessment (CCA) mechanisms in parallel to sense active transmissions: Preamble Detection (PD) and Energy Detection (ED) [21]. PD is based on the ability of decoding preambles which are transmitted at the minimum bit rate of the technology. If PD fails, the channel can also be sensed as busy by ED, that is, when the Received Signal Strength Indication (RSSI) measured is greater than a given threshold. For instance, in 802.11a this threshold is defined as 20 dB above the minimum 6 Mbps sensitivity [2].

Routing protocols usually broadcast periodical Hello messages in order to discover one-hop neighbors. Since broadcasting is usually done at the minimum transmission bit rate, any transmission of a one-hop neighbor will be detected by the PD mechanism. On the other hand, any transmission of a node whose Hellos cannot be correctly decoded will not be detected either by PD or by ED mechanisms. Thus, the Carrier Sensing range of node can be modeled as its one-hop neighborhood. This model only ignores the situations whereby simultaneous transmissions of two or more nodes out of the one-hop neighborhood are detected by the ED. This approximation is known as the capture threshold model or protocol model [22]. Using this model, we define the Contention Level, CL_i, of a node i as follows:

$$\mathrm{CL}_i = \mathrm{CN}^i + \sum_{\forall m \in N_1^i} \mathrm{CN}^m, \tag{14}$$

where CN^i is the portion of channel time consumed by node i (i.e., the transmitter) as defined in (13) and the summation includes the portion of channel time consumed by the one-hop neighbors, denoted by N_1^i, of node i. Hence, CL_j gives the contention level in the carrier sensing range or one-hop neighborhood of node i, where a value of 0 represents a free transmission channel and a value of 1 represents a totally occupied transmission channel.

3.3. Interference Level in Reception. Interference in reception is difficult to model at the network layer, since it depends on several physical parameters and phenomena, such as distance between nodes, transmission power, wireless propagation, receiver sensitivity, SNIR, data modulation and capture effect [23]. A commonly used model is called the interference range model [22]. In this model, interfering nodes are those situated at a distance from the receiver shorter than or equal to the Interference Range (IR), which can be obtained as follows:

$$\mathrm{IR} = \mathrm{CR} \times (1 + \Delta), \tag{15}$$

where CR is defined as the Communications Range and Δ is an additive parameter. In numerous studies, Δ takes a value of 1 and CR is defined as the one-hop neighborhood. Thus, IR is approximated as the two-hop neighborhood of the receiver [5, 24]. Our solution is based on this approximation, but in order to model interference in reception properly, we give weights to the channel occupancy of the interfering nodes according to their relative position regarding the sender and the receiver. We define the Interference Level, IL_{ij}, of a link ij as follows:

$$\mathrm{IL}_{ij} = \sum_{\forall m \in (N_1^j \setminus N_1^i)} 2 \times \mathrm{CN}^m + \sum_{\forall m \in (N_2^j \setminus N_1^i)} \frac{1}{2} \times \mathrm{CN}^m. \tag{16}$$

The first summation considers the interference caused by the hidden nodes for the transmitter i, that is, the one-hop neighbors of the receiver j which are not one-hop neighbors of the transmitter i. Due to packet collisions and retransmissions, the interfered link perceives an inflated channel occupancy with respect to the real channel usage of hidden nodes. We find by simulation an inflation factor of around 2 [25], which is aligned with results obtained in empirical works published in the literature [24, 26]. Hence, as shown in the first summation, we accordingly assign a weight of 2 to the channel load of hidden nodes in order to model this significant impact on performance.

The second summation takes into account the interference of the two-hop neighbors of the receiver j which are not one-hop neighbors of the transmitter i. The interference caused by two-hop neighbors strongly depends on the distance and the number of interfering nodes [25]. While a two-hop neighbor that is very close to the receiver can impact the channel occupancy in a way similar to a hidden node, further nodes may have no impact at all on performance. Intuitively, in most situations the impact on performance of these nodes would be lower than the impact of hidden nodes and contending nodes in transmission. On the other hand, failure to consider the load of these nodes would lead to interference underestimation. Hence, as shown in the second summation, we accordingly weight the channel load of two-hop neighbors by one half. This is a value between the weight for contending nodes in transmission (i.e., a weight of 1, see (14) and (17)) and a weight of zero, which would correspond to not taking the two-hop neighbor load into account.

3.4. WCIM Metric Definition. A node j computes the WCIM metric of the kth flow traversing link ij, denoted by $\mathrm{WCIM}_{ij,k}$, as follows:

$$\mathrm{WCIM}_{ij,k} = \frac{P_k}{\mathrm{BW}_{ij,k} \times \left(1 - \mathrm{CL}_i - \mathrm{IL}_{ij}\right)}, \tag{17}$$

where P_k is the average packet size of the kth flow of link ij, $\mathrm{BW}_{ij,k}$ is the bandwidth of the link ij for the kth flow, CL_i represents the contention level in transmission for node i and IL_{ij} is the interference level in reception for link ij. Both CL_{ij} and IL_{ij} are defined as a percentage of channel time and their sum cannot exceed 1. The denominator of $\mathrm{WCIM}_{ij,k}$, represents the available bandwidth of link ij for the kth flow of that link. Thus, $\mathrm{WCIM}_{ij,k}$, can be regarded as an estimation of the delay for transmitting a packet of size P_k through link ij.

Figure 1 illustrates an example of the nodes that contend with the transmitter i, the nodes that interfere the receiver j, and the weights assigned to each node to calculate the contention and interference levels of the link ij. Note that WCIM could be extended for multiradio environments in a simple way by considering only the contention and interference levels of the nodes which are transmitting in the same channel as the link ij.

Finally, the metric of a path p for a flow k, denoted by $\mathrm{WCIM}(p,k)$, is defined as the sum of all the link costs of the path

$$\mathrm{WCIM}(p,k) = \sum_{\forall ij \in p} \mathrm{WCIM}_{ij,k}. \tag{18}$$

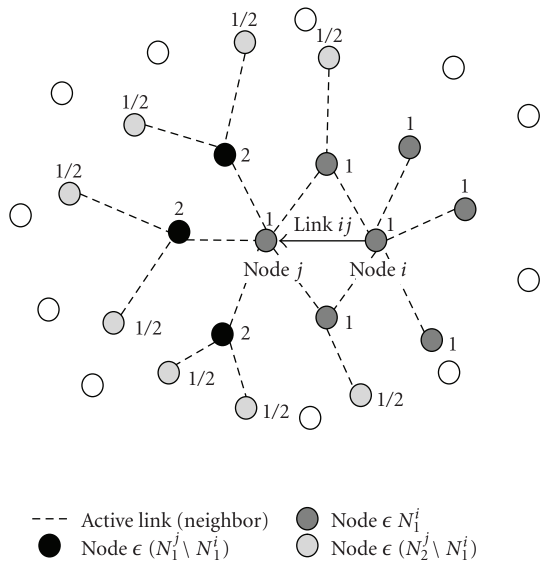


Figure 1: Example of WCIMs channel occupancy algorithm. The one hop neighbors of the transmitter i are weighted by 1, the hidden nodes of link ij by 2 and the two-hop neighbors of the receiver j by 1/2.

3.5. Routing Protocol Requirements. We now identify two requirements for the routing protocol to be used in conjunction with WCIM.

(i) The routing protocol must be on-demand. Load-aware metrics like WCIM vary with the number of active flows. Proactive routing protocols are not suitable for WCIM (or any other load aware metric) because these protocols periodically recompute routes, and the metric variations may cause network instability (e.g., route oscillations and collisions [27]). On-demand routing protocols avoid these problems since once a route is established, load changes will not lead to route recomputation.

(ii) The routing protocol should be flow based. Most routing protocols find routes to destination nodes, that is, given a destination node, all the flows sharing the same source or a same intermediate hop are routed through the same path or path segment, respectively. For load aware metrics like WCIM, such a routing approach limits the achievable performance, especially in scenarios where a node acts as a gateway to the Internet. Hence, WCIM requires flow based routing in order to exploit its benefits fully. Figure 2 gives an example of destination-based and flow based routing paradigms.

In order to implement and evaluate the WCIM metric, we have designed a reactive, flow based routing protocol on the basis of the Ad-hoc On-demand Distance Vector (AODV) routing protocol [28], one of the most popular reactive routing protocols for wireless multihop networks. The following section describes our integrated solution, which we call Flow-Based AODV (FB-AODV).

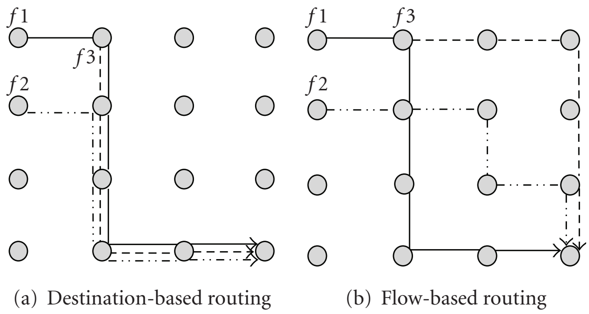


Figure 2: Example of destination- versus flow based routing. $f1$, $f2$, and $f3$ are three ordered flows with the same destination. In (a), all flows share the same path segment from the first common intermediate hop to the destination. In (b), flow based routing permits a better flow distribution in the network, thereby reducing the interference and contention suffered by each flow.

4. Flow-Based Ad-Hoc On-Demand Distance Vector (FB-AODV)

This section describes our routing solution, which comprises a flow based extension of AODV, denoted FB-AODV, and WCIM as the routing metric. Section 4.1 briefly overviews AODV. Section 4.2 presents how AODV is extended to enable flow based routing and to the use of the WCIM routing metric.

4.1. AODV Overview. When a node requires a route, AODV initiates a route discovery procedure by broadcasting Route Request (RREQ) messages. The routing metric is computed each time a node receives a RREQ message. The node accumulates the metric of the link from which the RREQ was received to the total path metric carried in the RREQ. If the routing metric computed is the minimum discovered so far, it saves the reverse route and continues broadcasting the RREQ. Otherwise, the RREQ is discarded. If on reception of a RREQ the node has a valid route entry to the demanded destination or is the destination itself, it sends a Route Reply (RREP) message back to the source node. Every node maintains route entries with next hop information that expire after a specified time if the path becomes inactive. When a link breaks along an active path, the node that detects this break creates a Route Error (RERR) message which reports the set of destinations that are now unreachable and sends it back to the source. Upon reception of the RERR message, the source may start a new route discovery. For connectivity maintenance purposes, each node can periodically broadcast Hello messages within a one-hop radius.

4.2. FB-AODV and WCIM Integration. We extend the basic, destination-based AODV route discovery to support flow based routing. FB-AODV routes packets on the basis of the destination address, the source address and the Type of Service (ToS) field used by the packets of each flow (i.e., each active route is only used for packets with same destination, source and ToS.) In order to integrate WCIM into FB-AODV, we add the following mechanisms to the routing protocol.

(i) Link Quality Estimation. Each node periodically collects information about the quality of the links to its neighbors in order to compute the bandwidth of link ij as per (11). The loss rate of the links, ETX_{ij}, is computed using the Hello-based estimation usually proposed for ETX metric implementations [29, 30]. The nominal link bit rate, LR_{ij}, is obtained by using the packet-pair technique proposed for the ETT metric computation [8].

(ii) Channel Occupancy Dissemination. The routing metric computation in (14) and (16) requires that the RREQ receiver knows the CN^m parameter (i.e., channel occupancy ratio) for all its one-hop and two-hop neighbors. Therefore, we define special Load messages, which are broadcasted with a TTL value of two hops. These messages have a size of 12 bytes and are sent only when a node notices a change in its load value (i.e., a new route is created or becomes expired). Therefore, as proved in Section 5.2, the overhead of these additional control messages is almost negligible.

(iii) WCIM Model. As mentioned above, the computation of ETX requires each node to add extra information in the Hello messages (i.e., IP address and loss rate estimation of each neighbor). Hence, using this information, a node can easily obtain the one- and two-hop neighbors of a link ij in N_1^i, N_1^j/N_1^i and N_2^j/N_1^i.

(iv) Flow Characteristics Encoding. We use the ToS field of the packets of a flow k to encode its average packet size, P_k, and its sending rate, FR_k, both of which are needed for WCIM computation.

Note that although WCIM is designed according to a cross-layer approach in order to take the impact of physical, MAC and application layers on the routing performance [31, 32] into account, all the parameters needed in our implementation are obtained at the network layer. Thus, while the design of our routing solution can be considered a violation of the layered architecture [33] (as indeed occurs with any routing metric other than the hop count metric), our implementation does not entail either the modification of other layers or the definition of shared databases or direct communication between different layers. Hence, our implementation can easily be integrated with commercial IEEE 802.11 products.

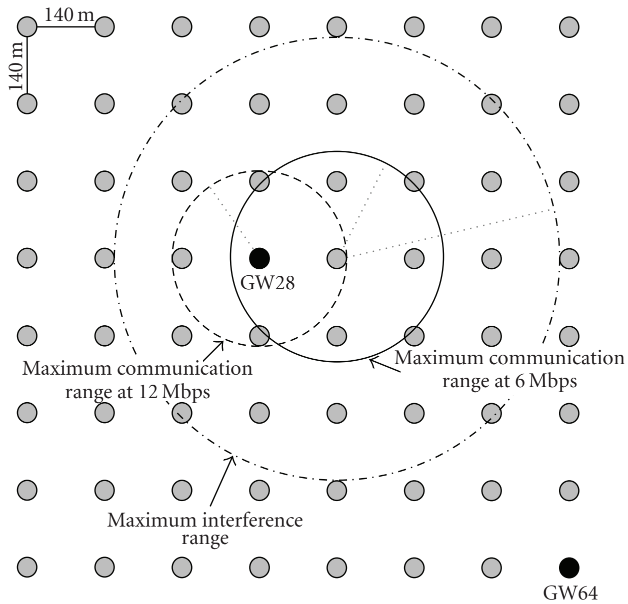


Figure 3: Simulation scenario.

Table 3: Fixed simulation parameters.

Parameter	Value or configuration
Propagation model	Two-ray propagation model
Fading	Ricean fading with factor 5
Transmission power	30 mW
PHY/MAC technology	IEEE 802.11a
Transmission rate of broadcast, preambles and ACKs	6 Mbps
Minimum sensitivity at 6 Mbps (Carrier sensing range using preamble detection)	−82 dBm in reception (197 meters)
Minimum sensitivity at 12 Mbps (Max. communication range at 12 Mbps)	−79 dBm in reception (167 meters)
Noise level (Max. interference range)	−95 dBm in reception (418 meters)
RTS/CTS mode	Off
Link bit rates	Randomly fixed at 6 Mbps or 12 Mbps
Type of flows	UDP, Constant-Bit-Rate, unidirectional
Random Number Generators (RNG)	4 independent RNGs: application, routing, MAC and PHY layer

5. Evaluation

We compare the performance of WCIM with other representative metrics reviewed in Section 2.2: Hop Count (denoted as HOPS from this point forward), ETT (which is link-aware) and ILA (which is load and interference-aware). We also study ALM (which is also link-aware) due to its interest as the routing metric proposed by the IEEE 802.11s standard. Section 5.1 describes the simulation scenario. Section 5.2 evaluates the overhead due to WCIM. Section 5.3 compares destination- and flow based routing solutions. Section 5.4 analyzes the performance of the routing metrics in a variety of scenarios. Finally, in Section 5.5 we discuss about the capacity of each routing metric to estimate performance of routes.

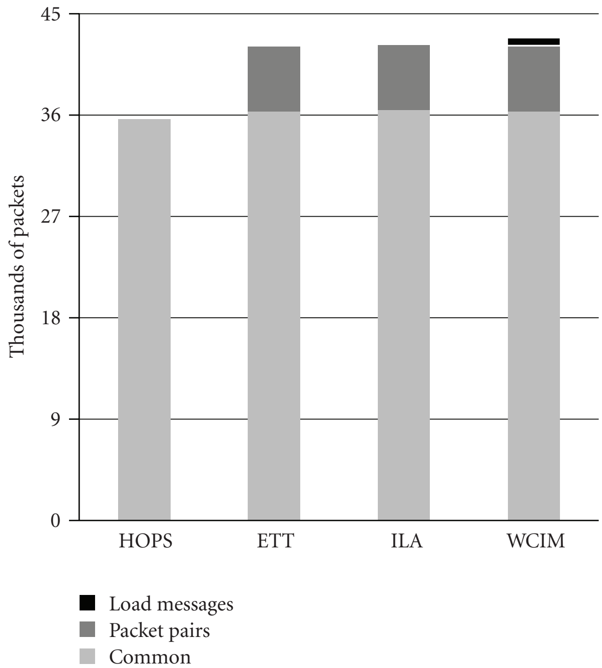
5.1. Simulation Platform and Scenario. Our evaluation is carried out by simulation, using OMNET++ v3.4b2, a discrete event simulator [34]. We chose OMNET++ because its wireless physical model is based on *the Additive SNIR Model*, which models carrier sensing and interference more accurately than other models, such as the *Capture Threshold Model* implemented by default in NS-2 [22, 35]. We implement the mechanisms presented in the previous section over a basic AODV implementation developed in a MANET framework for OMNET++ v3.4 [36]. We also integrate other public extensions which add support for 802.11a/g, bit error rate (BER) computation based on 802.11a/g modulations, Rayleigh fading channels and different types of propagation models [37]. Finally, OMNET++ uses random number generators based on the Mersenne Twister with a period of 2^{19937}-1, which ensures statistical validity [38].

The basic simulation scenario consists of 64 stationary nodes located in a 980 m × 980 m grid topology, as detailed in Figure 3. In Section 5.4 we also simulate two scenarios where the nodes are located using a random uniform distribution. Table 3 summarizes the main parameters of the simulations. We assume that each node uses an IEEE 802.11a radio interface [2].

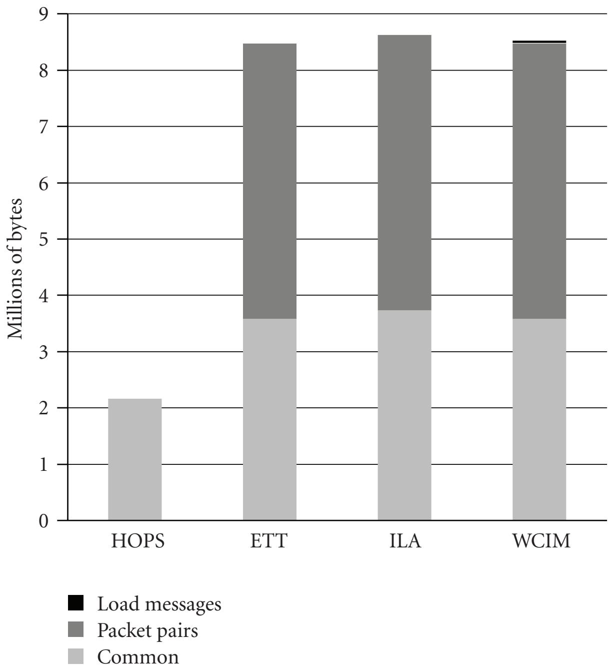
5.2. WCIM Overhead. We next evaluate the overhead of FB-AODV with HOPS, ETT, ILA and WCIM. With this purpose, we perform a 550-seconds simulation, where 15 flows are randomly created and deleted. Figure 4 shows the obtained total overhead in number of packets and in number of sent bytes.

As shown in Figure 4(a), the highest amount of messages corresponds to those labeled as “Common”, regardless of the metric. These messages include Hello, RREQ, RREP and RERR messages. However, as depicted in Figure 4(b), they do not consume a large bandwidth fraction, as the size of the messages is short (see Table 4).

Since the HOPS metric does not need the ETX and ETT extensions, the overhead of FB-AODV with this metric is significantly lower than that obtained with the rest of metrics. In fact, packet-pair mechanism is the main cause of overhead for ETT, ILA and WCIM, due to the size of the packet-pair messages. This mechanism sends one short and one long packet each minute for each pair of neighbors. In addition, ETX computation adds 8 bytes per each one-hop neighbor in the Hello messages, which are transmitted once per second. In addition to the signaling used by ETT, ILA requires the nodes to exchange load information using Hello messages [17]. Thus, ILA leads to a slightly higher overhead than ETT. On the other hand, instead of extending



(a) Overhead of FB-AODV in packets



(b) Overhead of FB-AODV in bytes

Figure 4: Overhead of FB-AODV: (a) in number of messages and (b) in number of sent bytes.

Table 4: Control messages of FB-AODV.

Message	Packet size (in bytes)
Hello	4
RREQ	20
RREP	24
RERR	12
Hello (ETT)	4 bytes + $8 \cdot N_1^i$
Packet-pair (short packet)	116
Packet-pair (long packet)	1468
Hello (ILA)	8 bytes + $8 \cdot N_1^i$
Hello (WCIM)	4 bytes + $8 \cdot N_1^i$
Load message	12

Hello messages as ILA does, WCIM computation requires the nodes to send Load messages each time a route variation (i.e., active route creation or expiration) is noticed. These messages are broadcast with a TTL of two hops. Figure 4(b) shows that the additional overhead of Load messages is almost negligible due to their short size.

5.3. Destination-Based versus Flow-Based Routing. As introduced in Section 4.2, flow based routing allows the routing protocol to apply load balancing in routes destined to the same node sharing a common source or intermediate node. This is a common situation in scenarios where a gateway concentrates the traffic to the Internet. In order to compare the performance of destination-based and flow based routing in such a case, we simulate a scenario with four active flows between nodes 1 and 64 (i.e., upper left and bottom right end nodes of the network, resp.,). These nodes are separated by a minimum of 14 hops. In the case of the classic AODV routing procedure based on destinations, the first flow creates a path which is followed by all the later flows. In the case of FB-AODV, we use different ToS in order to allow each flow to search for a particular route. The first flow starts at second 200, and every 50 seconds a new flow starts. The duration of the simulations is 500 seconds. Packets have a size of 1472 bytes and are sent with a constant rate of 500 kbps. Results are obtained as the average values from 100 simulations for each routing option. Figure 5 shows the goodput and end-to-end delay per active flow for classic AODV and FB-AODV for the four routing metrics considered (i.e., HOPS, ETT, ILA and WCIM).

As shown in Figure 5(a), using the classic AODV, the activation of the third and fourth flows (at seconds 300 and 350) causes severe congestion and link breaks, and significantly degrades the goodput and the delay per flow. However, using FB-AODV (see the corresponding results labeled FB-), the first three flows lead to a minor degradation, while the fourth causes less degradation than classic AODV. Note that even when using FB-AODV, the fourth flow leads to significant degradation, since there is an unavoidable bottleneck in the destination neighborhood. Nevertheless, FB-AODV improves classic AODV goodput by up to 45%, while delay is reduced by up to 65%.

The performance improvement of FB-AODV for ILA, which is a load aware metric, was expected, since FB-AODV allows load balancing in the network. However, results show that FB-AODV benefits load unaware metrics like ETT or HOPS to a similar degree. Since the ETT metric is aware of the link error rate, some links that became

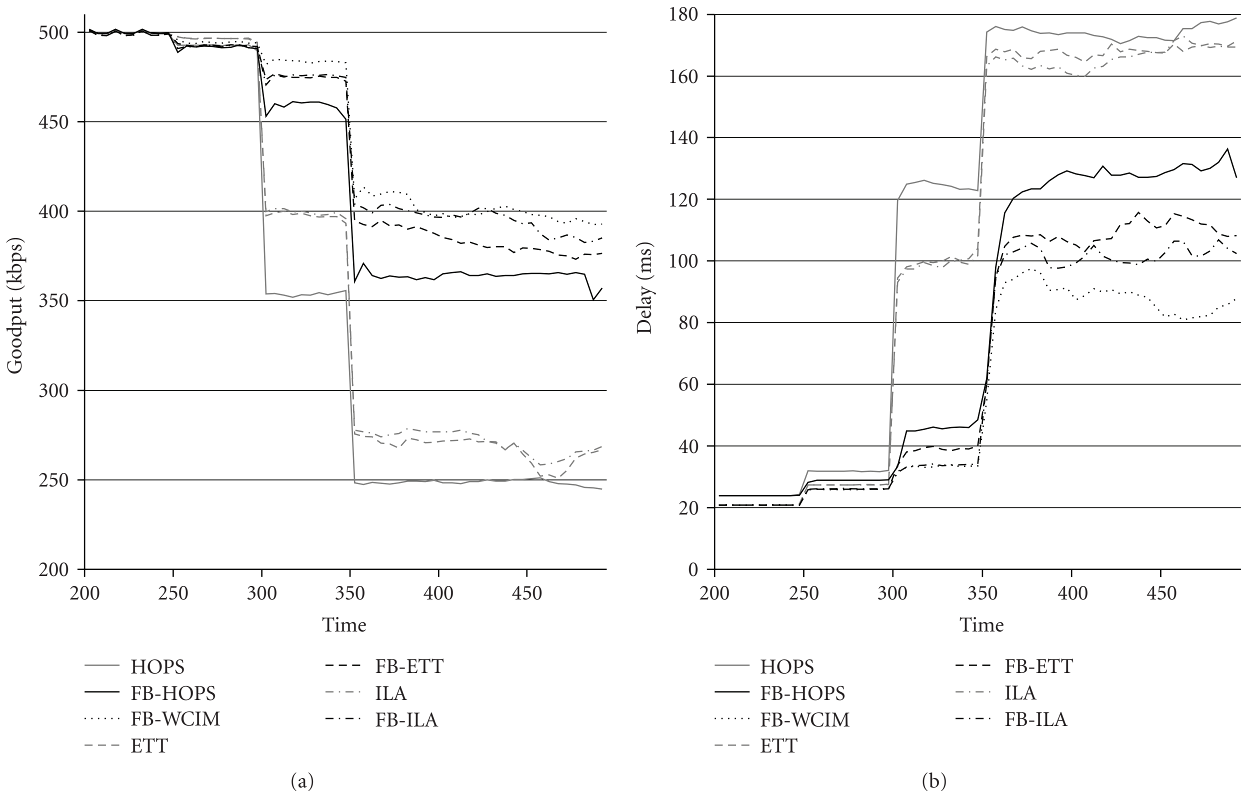


Figure 5: AODV versus FB-AODV. (a) Goodput per flow. (b) Delay per flow.

congested by the first flows are avoided in the route creation of the later ones. On the other hand, the HOPS metric leads to load balancing by chance: since in this scenario there are many possible routes with the same minimum number of hops, the probability of using different routes for each flow is high. Note that WCIM metric is only simulated using FB-AODV, since this is a requirement of its design.

Finally, comparing the results of the different routing metrics, we can see that ETT outperforms HOPS results both in goodput and delay. Since ETT is aware of the quality of the links, it chooses links with higher bit rates (i.e., 12 Mbps) thereby obtaining faster paths. On the other hand, FB-AODV allows load aware metrics like ILA and WCIM to balance the load, thus outperforming the ETT metric. In particular, WCIM metric obtains the best results in this scenario. In the following sections we discuss the differences between these four metrics in greater detail. Henceforth, the routing solution used will be FB-AODV for all routing metrics, for the sake of fair comparison (note that WCIM is the only considered routing metric that has been designed for flow based routing).

5.4. Routing Metrics Performance. We analyze the performance of HOPS, ETT, ALM, ILA and WCIM routing metrics in six main scenarios. Three types of flows are defined: $f1$ (sending rate of 75 kbps, packet size of 1472 bytes), $f2$ (50 kbps, 972 bytes) and $f3$ (10 kbps, 172 bytes). The number of active flows of each class is the same in each scenario. For each scenario, we analyze performance under different loads. We analyze the goodput (i.e., number of bytes correctly received at the destination per time unit), the packet loss rate (PLR) and the average end-to-end delay during the time interval in which all the flows are active. For each scenario, the results presented are the average of the results obtained from 100 simulations. Table 5 summarizes the main simulation parameters and characteristics of the four scenarios.

In the literature on WMN, routing metrics evaluation commonly consists in the definition of a unique type of flow with a fixed packet size (usually a middle size, e.g., 1000 bytes) and packet rate [6, 13, 16, 17]. We argue that it is more appropriate to take into account simultaneous flows with different characteristics in order to reflect better the variety of flows which may be present in a real network, and also consider the impact of load and interference according to the different types of flows (either the interfering or the interfered ones).

5.4.1. Scenario 1. Scenario 1 consists of six active flows with random source and destination. Figure 6 shows the results for this scenario in terms of the average length of the routes, the total goodput, the packet loss rate in and the average end-to-end delay (sum of the average delay of all the six flows). Note that goodput and the packet loss rate results are almost complementary. Henceforth, we focus the analysis on PLR results, since this complementary relationship is maintained in all the scenarios.

Table 5: Routing metrics performance: Scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Node location	Grid	Grid	Grid	Grid	Random	Random
Number of flows	6	6	6	15	6	15
Sources	Random	Random	Random	Random	Random	Random
Destinations	Random	Fixed: GW64	Fixed: GW28	Random	Random	Random
Flow duration	200 s	200 s	200 s	300 s	200 s	300 s
Simulation time	450 s	450 s	450 s	550 s	450 s	550 s
Analyzed interval	250 s–400 s	250 s–400 s	250 s–400 s	250 s–400 s	250 s–400 s	250 s–400 s
Load configurations	10	8	6	5	10	5
Minimum load	270 kbps	270 kbps	270 kbps	675 kbps	270 kbps	675 kbps
Maximum load	2700 kbps	2160 kbps	1620 kbps	3375 kbps	2700 kbps	3375 kbps

Results show that the HOPS metric always gives the worst performance. Under low load conditions, the HOPS metric leads to high delays, since it selects a higher number of links at 6 Mbps than the other metrics. The packet loss rate in these configurations is also high, since these slow links become congested. HOPS performance degrades with the increase of load, as shown in Figure 6.

On the other hand, ETT is link-aware, thus selecting links at 12 Mbps whenever possible, and obtaining good results with low load conditions both in PLR and delay. However, since ETT is interference and load unaware, these faster links also become congested and interfered with the increase of load conditions, which degrades ETT performance.

As expected, ALM and ETT performance is very similar, since both are based on the same link parameters. The main difference is that ALM is aware of link efficiency (i.e., physical and MAC layer overheads), thus preferring to select one hop at 6 Mbps rather than two hops at 12 Mbps, and in some cases favoring the creation of shorter routes than those of ETT. As shown in Figure 6, this difference is only appreciable for the maximum load considered, whereby ALM outperforms ETT.

ILA metric is interference and load aware, and its design favors the selection of routes totally free of interference, as described in Section 2.2.2. However, simulation results show that ILA only outperforms ETT performance under very high load conditions. ILA succeeds in routing packets through hops under low congestion and interference, but the paths selected are longer than those of the rest of metrics as shown in Figure 6(a). Thus ILA obtains a similar or better performance per hop than ETT, but a worse total performance due to its higher number of hops. Indeed, the delay performance of ILA under low load conditions is comparable to that obtained by using HOPS metric.

Finally, Figure 6 shows that the WCIM metric outperforms the rest of metrics in all load conditions, both in PLR and delay. In low load conditions, WCIM's routing strategy is similar to ETT and ALM, thus selecting routes through fast links. Under high load, WCIM balances the load in order to avoid highly interfered or congested links. Figure 6(a) shows that, in contrast to ILA, WCIM gives a good performance without increasing the length of the routes. This is a desirable property for WMNs, since shorter routes are in general more robust to link breaks and require fewer transmissions.

5.4.2. Scenario 2. In this second scenario we analyze a network where a node acts as a gateway to the Internet. Thus, we again route again six active flows with a random source, but this time with a common fixed destination (the node at the bottom right end of the network, denoted as GW64 in Figure 3). Figure 7 shows the results for this scenario.

The HOPS metric again gives the worst results in both PLR and delay due to its frequent use of slow and congested links. ETT, ALM and ILA results have a very similar PLR, even with the use of two very different routing strategies, as explained in the previous section. However, these differences become noticeable when comparing the delay performance, since ILA's longer routes lead to higher delays. As in the previous scenario, under low load conditions, the short and fast routes formed by ETT and ALM are more appropriate than the longer routes used by ILA, since link congestion remain low. In addition, in this scenario there is a bottleneck in the neighborhood of the common destination. Thus, ILA's routing strategy is also less effective under high load conditions, since there is no way of avoiding this bottleneck, which is the major source of interference and congestion in the network. Once again, WCIM gives the best performance, improving ETT and ALM results by adding load awareness, but without overestimating the effect of interference as in the case of ILA.

5.4.3. Scenario 3. The third scenario is very similar to the second one, but in this case the gateway is placed in the middle of the grid (GW28 in Figure 3). Thus, the average length of the routes becomes shorter (from an average of 7-8 hops in scenario 2 to an average of 4-5 hops in scenario 3). This fact drastically reduces the number of alternative routes that could be used by metrics like ILA and WCIM in order to apply load or interference-balancing. Furthermore, congestion in the neighborhood of the destination is increased. Figure 8 summarizes the results for this scenario.

The PLR performance of all four metrics in this scenario is very similar. As previously remarked, the short length

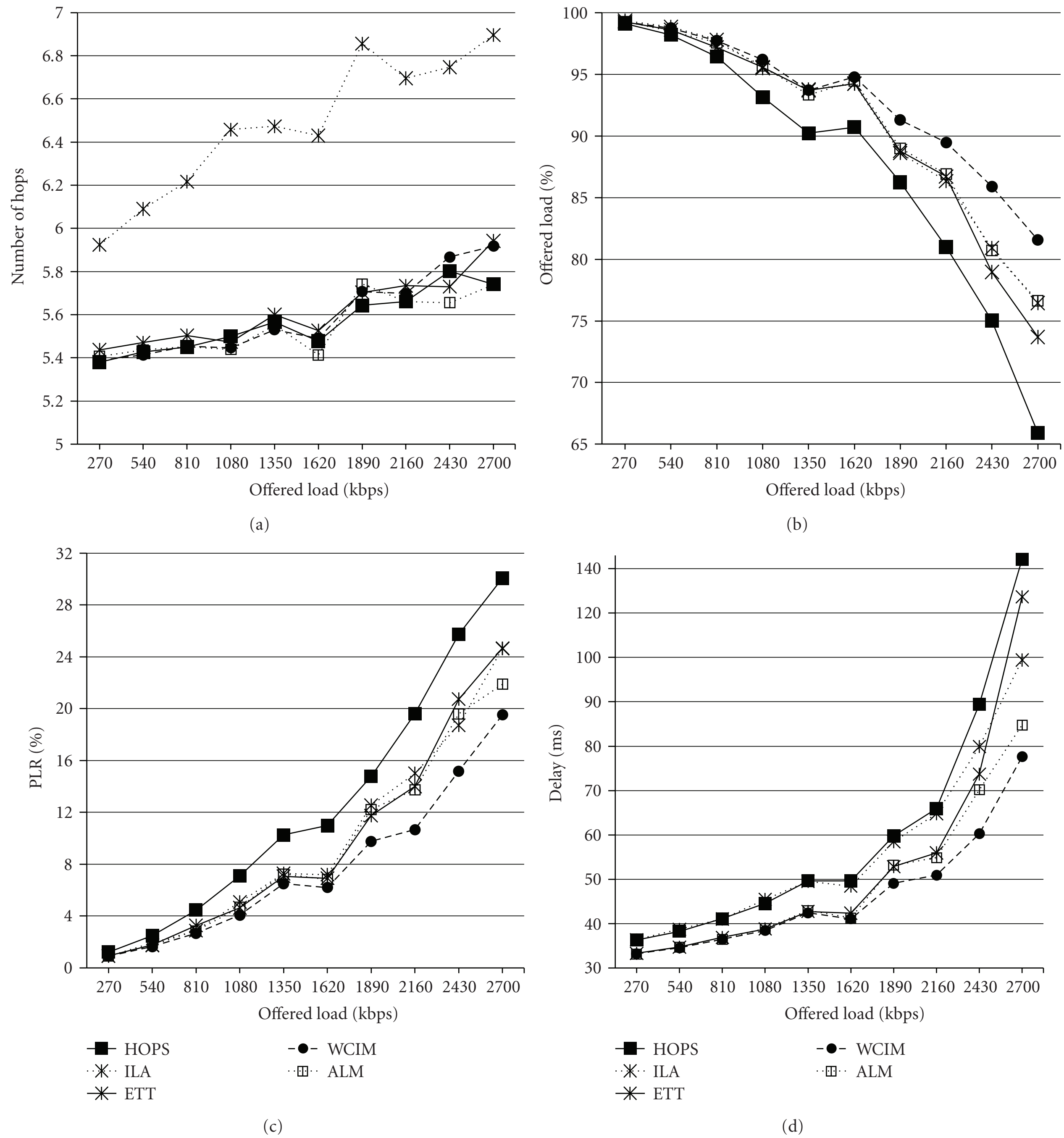
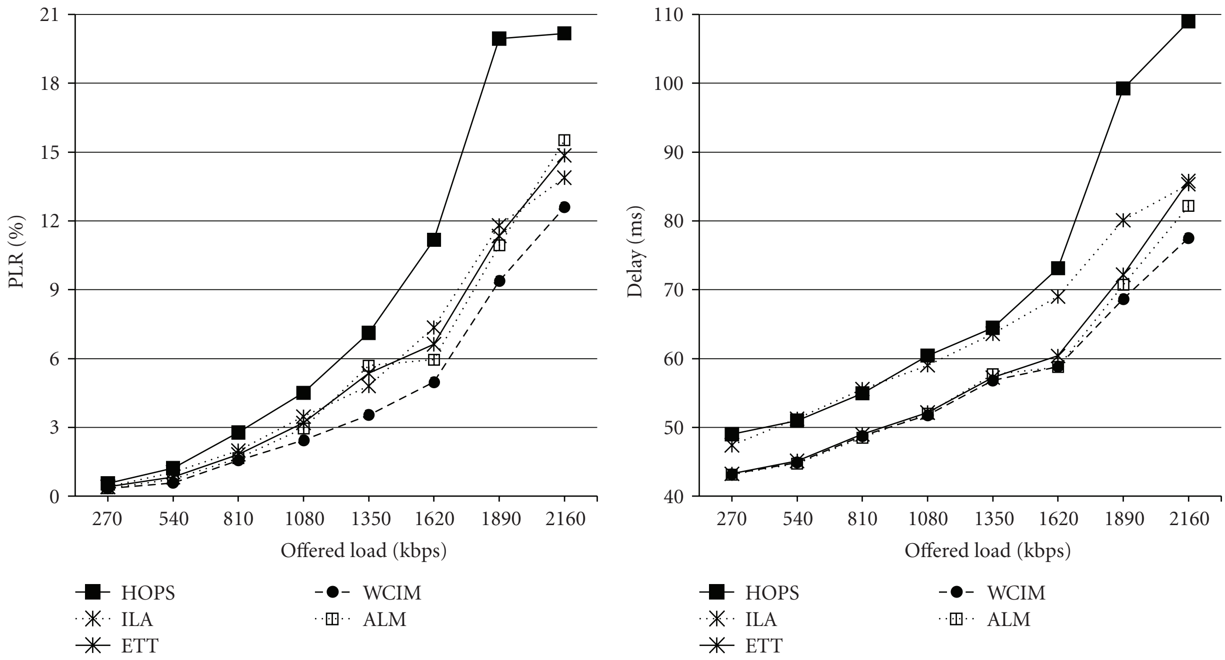


FIGURE 6: Scenario 1 main results. (a) Average route length. (b) Goodput. (c) Packet loss rate. (d) End-to-end delay.

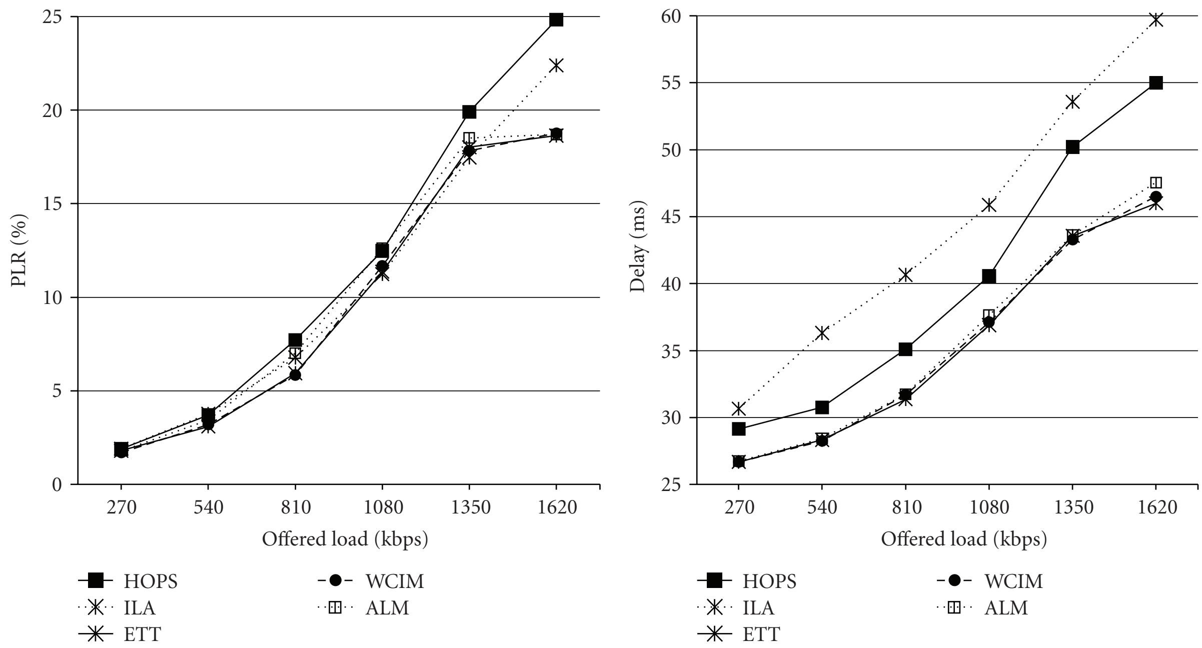
of the routes and the unavoidable interference in the neighborhood of the destination leave little margin for using different routing strategies. In some cases, even the HOPS metric yields only a slightly worse PLR performance. On the other hand, the delay performance of the four metrics shows some appreciable differences. ILA performance becomes even worse than HOPS performance, since in this scenario longer routes become totally inefficient. Indeed, the good performance of ETT and ALM metrics means that in such a scenario the best routing strategy consists simply in creating routes through the faster links. The results show that WCIM routes data in an equivalent way to these two metrics, thus obtaining almost the same performance as them.

5.4.4. Scenario 4. As in the first scenario, the fourth scenario is again based on random destinations, but this time analyzing the performance of 15 active flows, that is, 5 flows of each defined type. Since the network quickly becomes congested, we analyze only 5 load configurations. Figure 9 illustrates the results.



(a) (b)

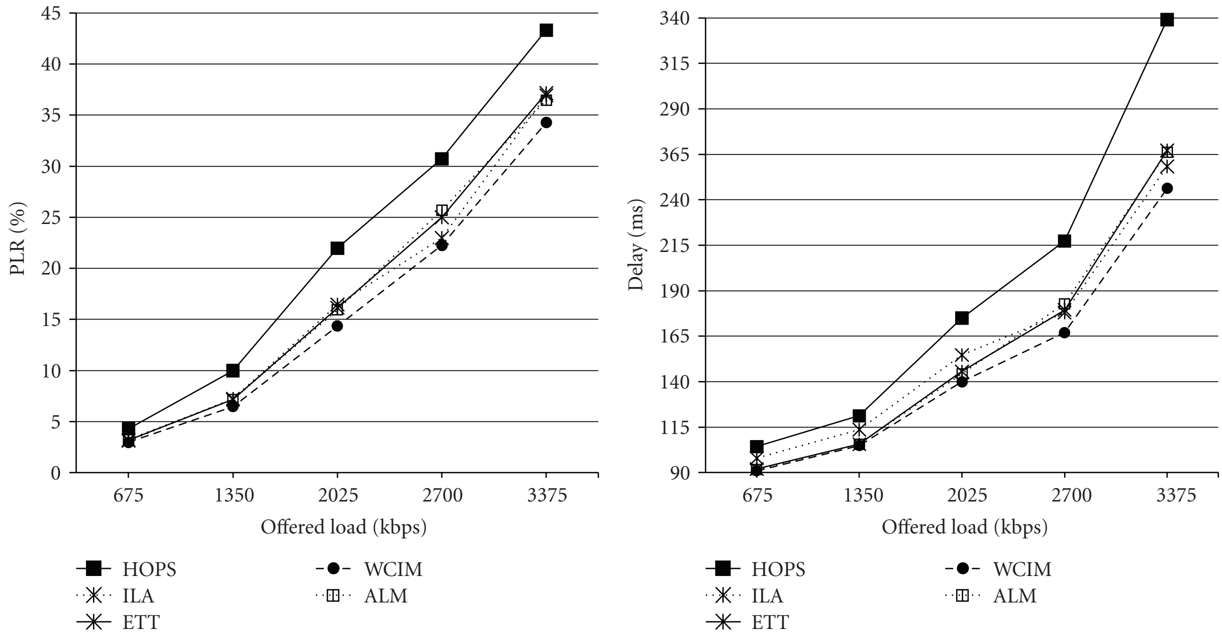
Figure 7: Scenario 2 results. (a) Packet loss rate. (b) End-to-end delay.



(a) (b)

Figure 8: Scenario 3 results. (a) Packet loss rate. (b) End-to-end delay.

Results are similar to those obtained in previous scenarios. The HOPS metric gives the worst performance, especially under high load conditions, while the other three metrics yield significantly better performance. ETT and ALM outperform ILA under low load conditions, mainly in delay measurements. However, ILA gives slightly better results with the increase of load. Indeed, ILA is more efficient than in the previous scenarios, since the characteristics of this scenario (i.e., random destinations and medium to high congestion) favor its routing strategy based on interference avoidance. Finally, WCIM again yields the best performance both in PLR and delay, outperforming the rest of the routing metrics.



(a) (b)

Figure 9: Scenario 4 results. (a) Packet loss rate. (b) End-to-end delay.

5.4.5. Scenario 5. Scenario 5 is based on the same traffic parameters defined in the first scenario (i.e., six random flows and ten load configurations), but in this case the nodes are located in the 980 m × 980 m area using a uniform random distribution. Since the number of neighbors is variable and sometimes scarce, the number of alternative routes that could be used by the different metrics also becomes limited. Thus, network congestion dramatically increases with offered load. The average results for this scenario are illustrated in Figure 10.

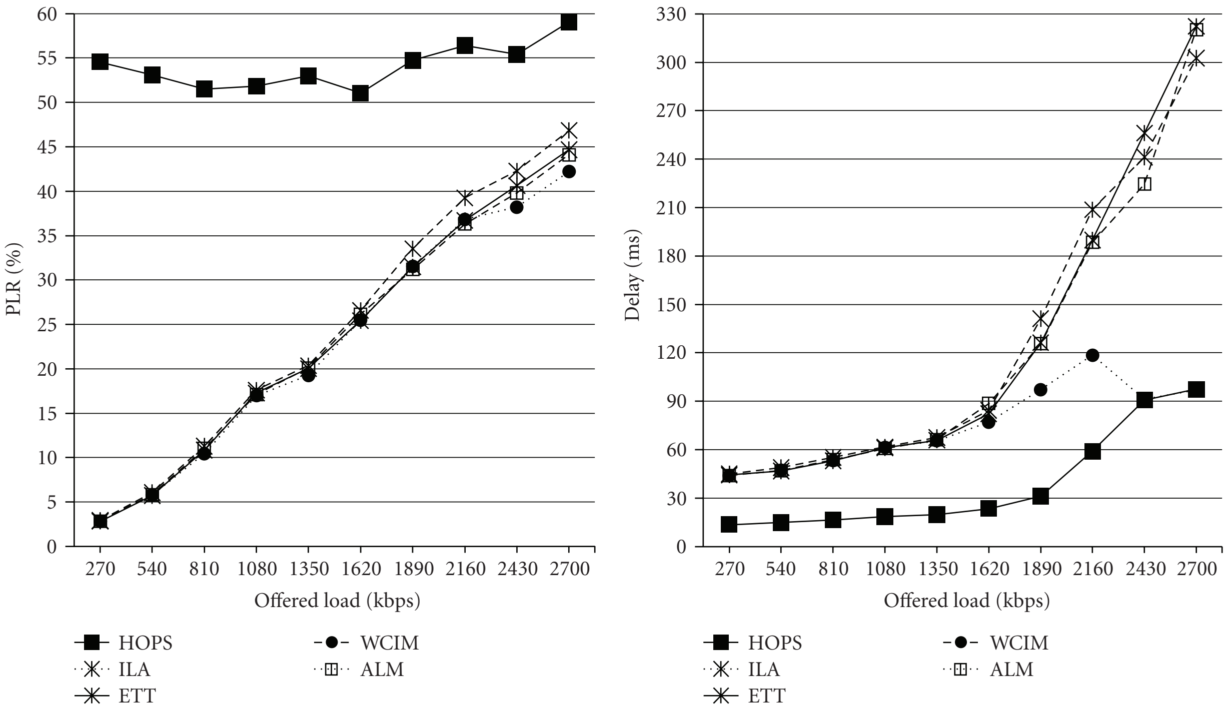
Figure 10 shows that HOPS yields a very different performance compared to the other metrics. Since neighbor discovery is based on HELLO messages, which are broadcast at 6 Mbps, unicast communication between neighbors is not always possible (recall that unicast link rates are randomly fixed at 6 Mbps or 12 Mbps). Thus, the use of HOPS involves some forward routes which are created by the broadcast flooding of RREQ messages; however, the corresponding backward routes cannot be successfully built since RREP messages are unicast. The other metrics do not suffer from this problem, since in order to discover the link rates they implement the packet-pair technique, which is based on periodical unicast signaling between neighbors. Hence, these metrics discard RREQ messages during route discovery if unicast communication with the RREQ sender is not possible.

For this reason, HOPS yields a PLR between 50% and 60% of the theoretical offered load throughout all the simulations. On the other hand, the end-to-end delay of HOPS remains low, since the network is less congested (as shown in Figure 11(a)) due to the routes which cannot be created.

While ETT, ALM and ILA metrics obtain similar results in this scenario, Figure 10(b) shows that WCIM yields low end-to-end delay with the increase of offered load. As previously explained, this scenario becomes very congested due to the random location of the nodes. This means that in some cases WCIM does not find any feasible route for new flows, that is, there is no route whose nodes have a sum of contention and interference levels smaller than 1 (see (17)). As shown in Figure 11(a), this yields a lower percentage of traffic sent load. In consequence, WCIM controls the increase of the PLR of the active flows, as illustrated in Figure 11(b). In this way, unlike HOPS, the PLR of the total offered load of WCIM remains similar to ETT, ALM and ILA, and even outperforms them with load increase, as shown in Figure 10(a). This interesting feature of WCIM is similar to the admission control mechanisms used for QoS assurance in WMNs [39].

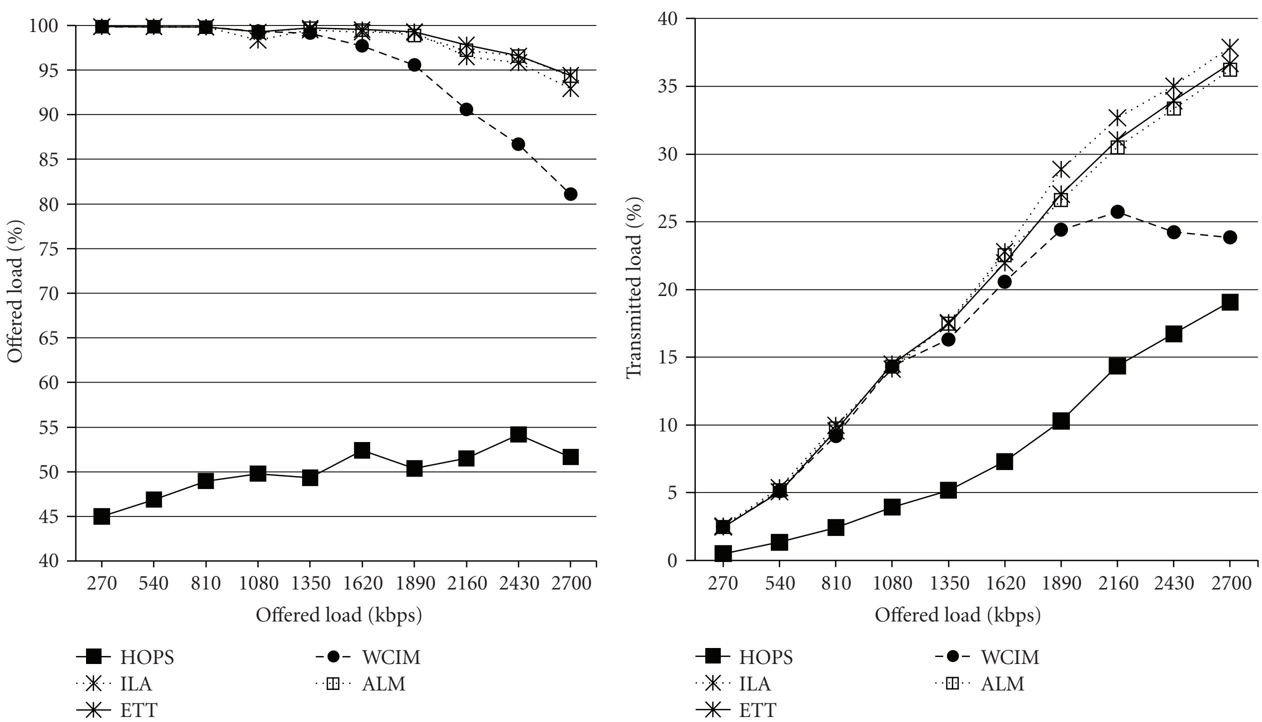
5.4.6. Scenario 6. Finally, the sixth scenario is also based on a random distribution of the nodes but now with the traffic parameters defined in the fourth scenario (fifteen random flows and five load configurations). Figure 12 summarizes the results obtained.

As in the previous scenario, HOPS and WCIM obtain a differentiated performance as regards the other three metrics. Once again, HOPS transmits less than the 50% of the offered load through the network due to unavailable routes, thus obtaining a high PLR and a low end-to-end delay. On the other hand, while decreasing the sent load due to congestion, WCIM yields a similar and even better PLR than the other three metrics as well as a significantly lower end-to-end delay.



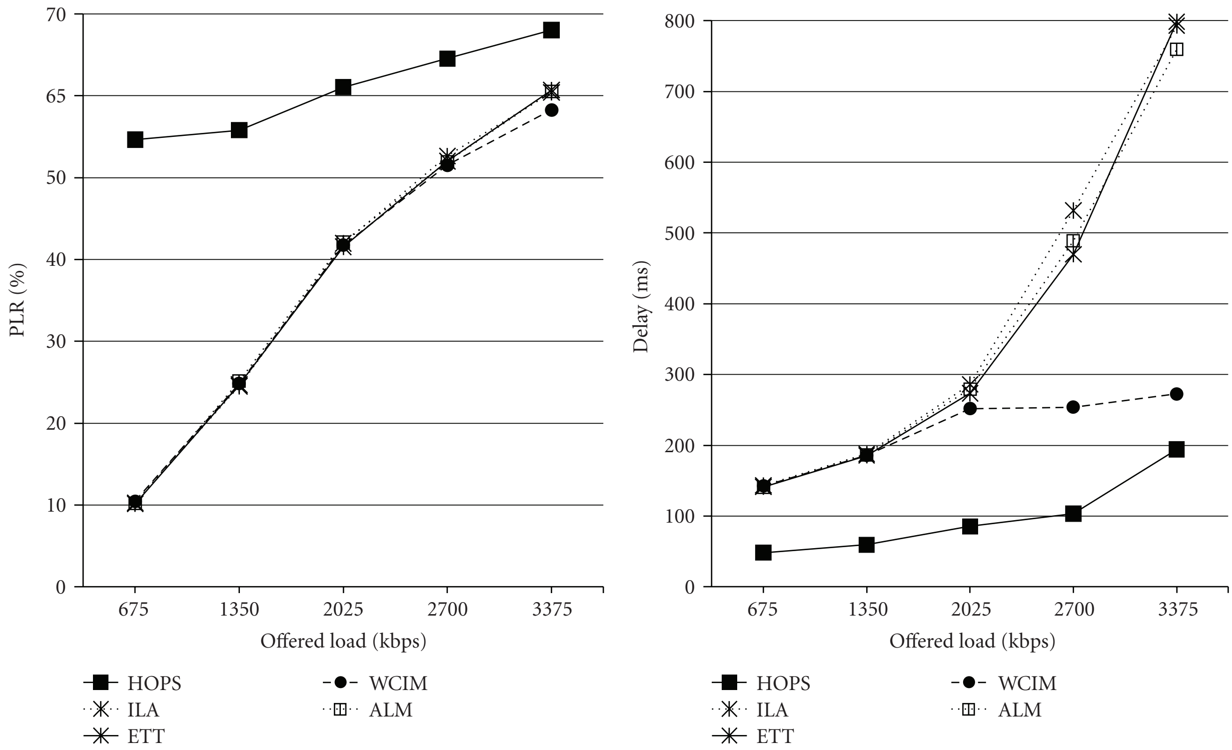
(a) (b)

Figure 10: Scenario 5 main results. (a) Packet loss rate. (b) End-to-end delay.



(a) (b)

Figure 11: Scenario 5 additional results. (a) Transmitted load. (b) Packet loss rate of transmitted load.



(a) (b)

Figure 12: Scenario 6 main results. (a) Packet loss rate. (b) End-to-end delay.

5.5. Routing Metrics as Performance Estimators. Finding the best route according to a set of performance parameters requires that the routing metrics give values to routes based on the expected performance of such routes. In this section we analyze whether HOPS, ETT, ILA and WCIM metrics reflect end-to-end delay, which is the reference performance parameter for these metrics.

We define three types of flows with random source and destination to be routed in the grid scenario: $f4$ (sending rate of 500 kbps, packet size of 1472 bytes), $f5$ (200 kbps, 972 bytes) and $f6$ (50 kbps, 172 bytes). The evaluation is carried out under three different initial load and interference conditions depending on the number of flows (zero, one or two flows) routed in the network. Then, another flow, which will be the flow under analysis, is started and routed. For this flow, and for each simulation, we obtain a pair of values for each considered routing metric: (i) the routing metric value which has already computed in the route discovery, and (ii) its average end-to-end delay. The duration of the flow under analysis is 200 s and we analyze 250 different simulations for each type of flow (i.e., $f4$, $f5$, and $f6$).

Figures 13 to 17 plot these pair of values for each simulation in the case of flow $f6$ (results obtained for $f4$ and $f5$ were very similar [25]). For a better comparison of the relationship between routing metric and end-to-end delay values, the pairs are ordered in the horizontal axis by the routing metric value (from minimum to maximum value).

Figure 13 shows the results obtained for the HOPS metric. It can be easily seen that the number of hops of a path

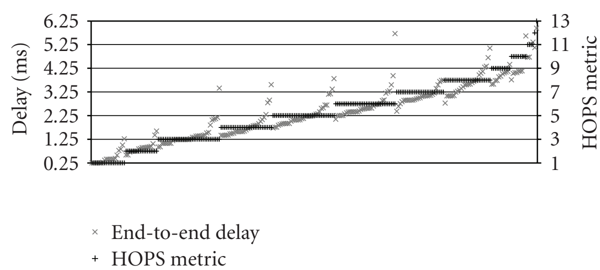


Figure 13: Comparison of HOPS metric and end-to-end delay variations ($f6$).

has an inaccurate relationship with its end-to-end delay. The HOPS metric is unaware of link characteristics, load or interference, which may significantly affect performance.

Figure 14 shows the same analysis for ETT. The performance of ETT metric as an end-to-end delay estimator is on average better than the HOPS metric, due to its link-awareness. However, since ETT does not consider the load and interference of the links, there are some cases where routes with the same or similar ETT metric lead to very different end-to-end delays. In addition, the ETT metric does not consider the influence of IEEE 802.11 physical and MAC overhead on performance, which is more significant in fast links than in slow ones.

As shown in Figure 15, the ILA metric behaves as a poor performance estimator. We can see two main regions in

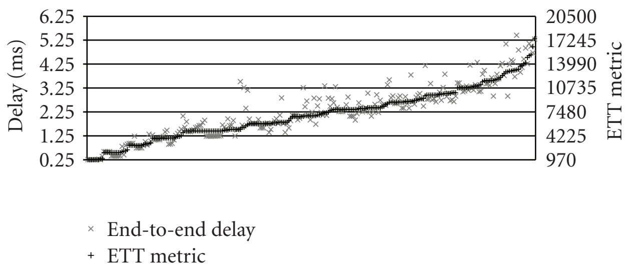


Figure 14: Comparison of ETT metric and end-to-end delay variations ($f6$).

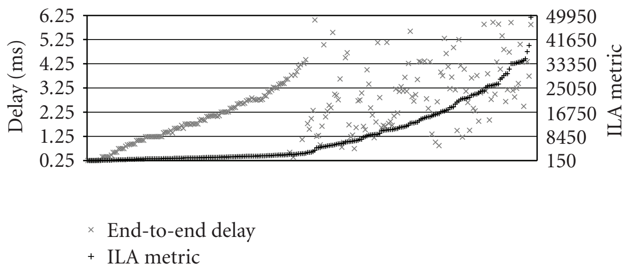


Figure 15: Comparison of ILA metric and end-to-end delay variations ($f6$).

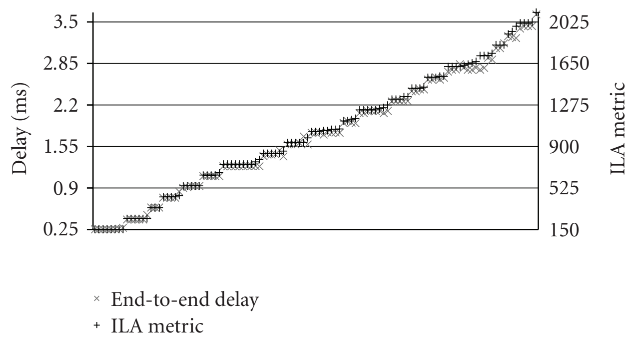


Figure 16: ILA regions: (a) Routes under no interference.

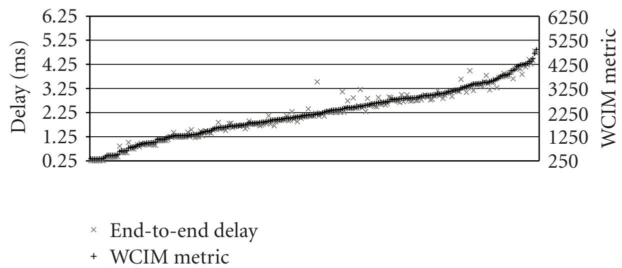


Figure 17: Comparison of WCIM metric and end-to-end delay variations ($f6$).

Figure 15. The results on the left side of the figure correspond to routes free of interference. In such cases, ILA algorithm is equivalent to the ETT metric. In this region (see Figure 16), ILA accurately reflects end-to-end delay, since in the absence of interference the end-to-end delay basically depends on link rates. However, results on the right side of Figure 15 correspond to routes that include interfered links. For such routes, ILA is unable to reflect the real impact of interference on the performance of the routes. The right side of Figure 15 shows how in this region the ILA metric and end-to-end delay variations become completely disassociated.

Finally, Figure 17 shows the results of this analysis for the WCIM case. Since it considers the load and interference of the links, WCIM clearly outperforms ETT. There are still some specific situations in which routes with a similar WCIM metric yield a different performance. The reasons for this behavior include inaccuracies in modeling interference. Nevertheless, assuming that the path cost using WCIM routing metric expresses the end-to-end delay for the packets of a flow in microseconds, WCIM can be considered as a reliable estimator of the average end-to-end delay for that flow through a given path. This is an interesting feature, for instance in order to route flows with delay requirements.

Table 6 shows the normalized standard deviation of the ratio between the end-to-end delay and the routing metric value for each type of flow. This parameter is a measure of the ability of each routing metric to predict the performance of the routes in terms of delay (ideally, the ratio between end-to-end delay and routing metric value should be constant, and hence its standard deviation should be zero). The results obtained corroborate the previous analysis and show how WCIM has greater reliability as an end-to-end delay estimator than the rest of routing metrics considered.

Table 6: Standard deviation of delay/metric ratio (expressed as a percentage of the average).

Routing metric	$f4$ (Large packets)	$f5$ (Medium packets)	$f6$ (Short packets)
HOPS	18%	20%	28%
ETT	7%	8%	19%
ILA	54%	61%	76%
WCIM	5%	5%	9%

For long packets, except in cases of heavy congestion or interference, the main factors affecting delay are the link bit rates and the number of hops of a path. Thus, ETT results are in average similar to those for WCIM. However, in the case of short packets, the link transmission times are small. Thus, interference, both congestion and link efficiency affect the total end-to-end delay more significantly. Since WCIM considers all these parameters, it significantly outperforms ETT results for short-packet flows.

6. Conclusions and Future Work

In this paper we focus on the impact of routing metrics on performance in 802.11-based WMNs. We first survey the most relevant state-of-the-art routing metrics for these networks. We conclude that a comprehensive solution considering all the relevant phenomena affecting the performance of a path in WMNs is still needed. Then we present a novel routing metric, WCIM, which combines link and load awareness using a weighted model of contention and interference based on IEEE 802.11 physical and MAC layer mechanisms. By means of simulation, we analyze the performance of WCIM in a variety of scenarios and compare it with that of other four representative routing metrics: Hop Count, ETT, ALM and ILA. Our solution is built on the basis of a flow based AODV protocol, which obtains up to 40%–60% better performance than the classical destination-based AODV, even for load unaware routing metrics. For the sake of fairness, the comparison of routing metrics is carried out using the flow based AODV routing protocol.

Simulations in a grid scenario show that the shortest-path Hop Count routing leads to a very poor performance due to its link-, load and interference-unawareness. On the other hand, ETT's routing strategy, which is based on the selection of fast links, gives good results especially in scenarios which make load balancing difficult (e.g., multipoint-to-point scenarios). However, ETT suffers significant degradation under high load due to its load and interference-unawareness. ALM leads to very similar results, since it is based on the same link parameters. ALM estimates the efficiency of IEEE 802.11 link rates, but unlike WCIM it is based on a constant probe packet size. On the other hand, ILA selects significantly longer paths than other metrics, because ILA tends to select links totally free of interference. Thus, ILA gives a poor performance even in low load conditions. WCIM outperforms the other considered metrics in almost all cases. Its routing strategy performs well both in low and high load conditions by selecting paths of low interference and congestion, but also a low number of hops. WCIM can actually be considered as a reliable estimator of the average end-to-end delay, which makes it possible to route flows through the best paths in terms of this performance parameter.

Simulations in a random scenario show that with the increase in congestion WCIM operates in a way equivalent to an admission control mechanism, due to the scarceness of available routes. This is an interesting feature for controling the impact of new routes on the performance of active flows.

We implement and perform some initial evaluations of WCIM and FB-AODV in a real testbed. For the implementation of WCIM, we leverage the Linux Routing Policy DataBase (RPDB) [40], which allows the creation of routes in most wireless routers according to different IP parameters (e.g., destination address, source address or Type of Service of a flow). As a subsidiary contribution of this paper, our implementation of WCIM and FB-AODV for Linux-based platforms is publicly available under GPL license [41].

We are currently investigating strategies for adapting WCIM for multiradio WMNs. An easy extension for these networks can be based on identifying the channel used in each link, which enables the congestion and interference level of a link to be computed. However, there are other challenges related with routing in multiradio networks, such as considering the channel diversity throughout a path in order to minimize intra-flow interference [20] or obtaining a proper solution for the Joint Channel Assignment and Routing (JCAR) NP-hard problem [42].

Finally, the IEEE 802.11s draft standard defines the ALM routing metric as mandatory, but offers the option of using other routing metrics by means of the Extensible Path Selection Framework [9, 20]. Hence, we plan to investigate the use of WCIM as a routing metric for IEEE 802.11s-based WMNs. In fact, IEEE 802.11s mandates support for an AODV-based routing protocol, which is a routing solution aligned with that used in conjunction with WCIM, as presented in this paper.

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